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The role of climate change in regulating Arctic permafrost peatland hydrological and vegetation change over the last millennium

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Abstract

Climate warming has inevitable impacts on the vegetation and hydrological dynamics of high-latitude permafrost peatlands. These impacts in turn determine the role of these peatlands in the global biogeochemical cycle. Here, we used six active layer peat cores from four permafrost peatlands in Northeast European Russia and Finnish Lapland to investigate permafrost peatland dynamics over the last millennium. Testate amoeba and plant macrofossils were used as proxies for hydrological and vegetation changes. Our results show that during the Medieval Climate Anomaly (MCA), Russian sites experienced short-term permafrost thawing and this induced alternating dry-wet habitat changes eventually followed by desiccation. During the Little Ice Age (LIA) both sites generally supported dry-hummock habitats, at least partly driven by permafrost aggradation. However, proxy data suggest that occasionally, MCA habitat conditions were drier than during the LIA, implying that evapotranspiration may create important additional eco-hydrological feedback mechanisms under warm conditions. All sites showed a tendency towards dry conditions as inferred from both proxies starting either from *ca.* 100 years ago or in the past few decades after slight permafrost thawing, suggesting that recent warming has stimulated surface desiccation rather than deeper permafrost thawing. This study shows links between two important controls over hydrology and vegetation changes in high-latitude peatlands: direct temperature-induced surface layer response and deeper permafrost layer-related dynamics. These data provide important backgrounds for predictions of Arctic permafrost peatlands and related feedback mechanisms. Our results highlight the importance of increased evapotranspiration and thus provide an additional perspective to understanding of peatland-climate feedback mechanisms.

Keywords

Testate amoeba, plant macrofossil, hydrology, vegetation, permafrost peatlands, last millennium, MCA, LIA, recent warming

34

35 **Introduction**

36 High-latitude peatlands play a critical role in the global biogeochemical cycle, through which they also
37 contribute to climate dynamics (Frolking and Roulet, 2007). Temperature and moisture balance are key
38 factors modulating peat accumulation (Carroll and Crill, 1997; Davidson and Janssens, 2006; Ovenden,
39 1990). Global warming, especially amplified warming in high-latitude regions (IPCC, 2013), is expected
40 to directly stimulate photosynthesis and net primary productivity (NPP) in high-latitude ecosystems
41 because of increased growing season length (Charman et al., 2013). Thus, peat accumulation is expected
42 to accelerate too (Loisel and Yu, 2013). However, higher temperatures also increase peat decomposition
43 rates through accelerated microbial activity (Dorrepaal et al., 2009; Ise et al., 2008), yet there is evidence
44 from the past that during warm periods the increase in NPP exceeded the potential increase in
45 decomposition (Charman et al., 2013). Climate scenarios for high latitudes predict that mean summer
46 precipitation will increase in the future (Collins et al., 2013), which could be beneficial for peat
47 accumulation. However, increases in precipitation may be offset by increases in evapotranspiration under
48 higher temperatures (Yu et al., 2009). Also, seasonal droughts may reduce NPP and increase
49 decomposition (Yu et al., 2009). Moreover, habitat-specific plant functional types (PFTs) that
50 characterise different peatlands (fens and bogs) have different NPP dynamics and the distribution of
51 these communities can exert a control on peat accumulation patterns (Tuittila et al., 2012). While climate
52 may directly affect plant productivity and decomposition, it may also have larger-scale impacts on the
53 geographical distribution of peatland types (Väliranta et al., 2015).

54 Arctic permafrost peatlands are sensitive to climatic changes (Gałka et al., 2017a; Lamarre et al., 2012;
55 Swindles et al., 2015a; Teltewskoi et al., 2016; Tremblay et al., 2014) and at the same time, they affect
56 local microclimate, hydrology, vegetation, peat and carbon accumulation and these non-climatic factors
57 again influence the degradation and aggradation of permafrost (Zuidhoff and Kolstrup, 2000). Due to
58 pronounced microtopography and persisting ice, eco-hydrological processes and therefore peat
59 accumulation patterns in permafrost peatlands are very complex (Oksanen, 2006; Oksanen et al., 2001),
60 making the evaluation of climate change impacts on these environments challenging. Northern
61 Hemisphere mean annual temperature for the last 30- and 50-year periods is likely higher than any other
62 preceding equally long measurement period during the past 800 years (Masson-Delmotte et al., 2013).
63 Permafrost ground temperature monitoring studies have documented a rising trend over the last 20-30
64 years and observations suggest permafrost thaw in the southern margins of the permafrost area (Brown
65 and Romanovsky, 2008; Johansson et al., 2011; Sannel et al., 2016). Even though these observations are
66 not ubiquitous (Brown and Romanovsky, 2008), a widespread permafrost thaw can be expected as a

consequence of global warming. It may be speculated that Arctic permafrost peatlands are on the edge of their climatological niche and have low potential to remain stable under future climate changes (Bosio et al., 2012). One presumption is that when permafrost thaws or if the active layer deepens considerably, permafrost areas become large CO₂ sources due to accelerated decomposition rates (Abbot et al., 2016; Koven et al., 2011; Schadel et al., 2016). It is suggested that these dynamics may be one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere in the future (Schuur et al., 2008). However, because of the scarcity of information and data, disentangling the links between permafrost peatland vegetation, hydrology and climate, the future balance of NPP and decomposition processes in permafrost peatlands has remained uncertain. These coupled dynamics can be investigated by comparing palaeoecological data to documented climate epochs such as the Medieval Climate Anomaly (MCA) from *ca.* AD 950-1200, the Little Ice Age (LIA) from *ca.* AD 1400-1850, and recent warming since the late 19th century (e.g., Cook et al., 2004; Esper et al., 2002; Hanhijärvi et al., 2013; Wilson et al., 2016).

In this study we investigated past hydrological changes and associated variations in vegetation composition during the last millennium in four permafrost peatlands. We used two different proxies; testate amoebae (Amesbury et al., 2016; Charman et al., 2007; Swindles et al., 2015b) and plant macrofossils (Väliranta et al., 2007; 2012) to reconstruct past moisture conditions and vegetation history, which enabled cross validation of results and therefore more dependable data interpretation (Loisel and Garneau, 2010; Väliranta et al., 2012). Using ¹⁴C and ²¹⁰Pb dating, we linked detected changes to known climate periods. Replicate records from the same peatland and/or close-by regions allowed us to evaluate whether detected changes were climate-driven and regional or forced by autogenic factors (Mathijssen et al., 2016; 2017; Swindles et al., 2012). Our hypotheses were 1) that permafrost thawing triggered by warm climate conditions (e.g., MCA and recent warming), is reflected in proxy records as a change towards wetter plant communities and more hydrophilic testate amoeba assemblages, and that 2) permafrost aggradation under colder climate conditions such as LIA results in dry conditions through raising of the peat surface. Furthermore, we evaluate whether and how the peatland response to MCA warming differs from the on-going recent warming.

Study sites

Our four study sites are located in two regions: two sites (Indico and Seida) are located in the discontinuous permafrost zone of Russia whereas the other two (Kevo and Kilpisjärvi) are in the sporadic permafrost zone of the Finnish Lapland (Fig. 1 and Table 1).

Indico and Seida are located in the Arctic Northeast European Russian tundra. The peat plateaus in these

two peatlands are elevated a few metres from the surrounding mineral soil and the vegetation is dominated by shrub-lichen-moss communities, such as *Betula nana*, *Rhododendron tomentosum*, *Empetrum nigrum*, *Sphagnum fuscum*, *Polytrichum strictum*, *S. lindbergii* and sedges *Eriophorum* spp. Compared to Seida, Indico presents extensive areas covered by lichens and mosses with a lower shrub layer. Large bare peat surfaces occur on both sites (Repo et al. 2009). At the two sites in Finnish Lapland, Kevo and Kilpisjärvi, the peatlands are characterised by separate permafrost mounds a few metres high and surrounding wet flarks. The mound vegetation is dominated by dwarf shrubs, such as *Betula nana*, *Empetrum nigrum*, *Rubus chamaemorus* and bryophytes *Polytrichum strictum* and *Dicranum* spp. Different *Sphagnum* species such as *S. fuscum*, *S. balticum*, *S. majus* and *S. riparium* occur along a hydrological gradient from dry hummock to wet hollow and *Eriophorum* spp. are also present.

Materials and methods

Sampling

In total, six active layer peat cores (Table 1) were collected from the four permafrost peatland sites using a Russian peat corer with a diameter of 5 cm. In Indico, three replicate peat cores (Ind1-3) were collected along a transect from the centre to the margins of the site to assess potential differences in sensitivity across the peatland surface. A single core was collected from each of the other sites. Individual cores were wrapped in plastic and transported to the laboratory in sealed PVC tubes and stored in a freezer. The cores were later defrosted and sub-sampled in 1-cm or 2-cm thick slices for further analyses. In some cases, analysis of both proxies from the same sample was not possible due to a lack of material. When this occurred, analysis was carried out using stratigraphically adjacent samples. In core 'Sei' from Seida the limited amount of material meant that only testate amoeba analysis was possible.

Chronology

Eighteen bulk peat samples were sent to the Finnish Museum of Natural History (LUOMUS, Helsinki, Finland) and the Poznan Radiocarbon Laboratory (Poznan, Poland) for accelerator mass spectrometry (AMS) ^{14}C dating (Table 1). Bulk peat samples were used because of high decomposition of some peat sections, which made picking out known macrofossils very difficult or impossible. Additionally, a recent study suggested that there is no significant difference between ages derived from bulk material and plant macrofossils in these settings (Holmquist et al., 2016). The chronology of the top parts of three peat cores were determined using ^{210}Pb dating (Table 1). The samples were processed at the University of Exeter, UK. A dry ca. 0.2-0.5 g subsample from each 1-cm interval was analyzed for ^{210}Pb activity after spiking

with a ^{209}Po yield tracer. The procedure followed a modified version of Ali et al. (2008). An age-depth model for each core was developed using CLAM 2.2 (Blaauw, 2010) in R version 3.2.4 (R Core Team, 2014), with ^{14}C ages internally calibrated using the INTCAL 13 calibration curve (Reimer et al., 2013). ^{210}Pb ages were obtained through the Constant Rate of Supply model (CRS) (Appleby and Oldfield, 1978), which was chosen over the Constant Initial Composition model because there was a subsurface maximum in ^{210}Pb activity in these three cores, suggesting that the peat accumulation rate has not been constant over time. Both ^{14}C and ^{210}Pb dates were included in the final age-depth models (Fig. 2). A smooth spline method was selected to develop the age-depth models with the exception of core Kev BS, which yielded age reversals when the default smoothing parameter 0.3 of CLAM model was employed and relatively large deviations of the calibrated ^{14}C dates to the age-depth model curve when changing this parameter, so a linear interpolation method was used instead for that core. Calibrated radiocarbon ages were rounded to the nearest 5 years. Negative ages indicate post-bomb ages (i.e. -50 cal. BP = AD 2000). In this study we focused solely on the time period of the last millennium.

Testate amoeba and plant macrofossil analysis

Testate amoeba sample preparation procedure followed a modified version of Booth et al. (2010). Samples were boiled in distilled water for 15 minutes. Samples were sieved using a 180- μm mesh instead of the standard 300- μm mesh as some materials contained a large quantity of decomposed plant detritus. All samples were back-sieved using a 15- μm sieve. Materials retained on the 15 μm sieve were centrifuged at 3000 rpm for 5 minutes. 50-100 individual testate amoeba shells for each sample were counted and identified to species level or 'type' under a light microscope with 200-400 \times magnification. Taxonomy followed Charman et al. (2000), but occasionally online sources were used to aid identification (<http://www.arcella.nl/>; user.xmission.com/~psneeley/Personal/FwrPLA.htm). Occasionally the lower parts of the peat sections were highly decomposed and decomposed plant material hindered testate amoeba identification. These samples were treated with 5% KOH to disaggregate and remove fine organics before sieving (Barnett et al., 2013; Charman et al., 2010). However, because the test count did not reach 50 specimens in these deeper samples, they were not included in the water-table depth (WTD) reconstructions.

For plant macrofossil analysis, volumetric samples (2-5 cm^3) were gently rinsed under running water using a 140- μm sieve. No chemical treatment was necessary. Remains retained on the sieve were identified and proportions of different plant types were estimated using a stereomicroscope. Further identification to species level was carried out using a high-power light microscope following Văliranta et al. (2007). In addition to identifiable plant remains, the proportion of unidentified organic matter

(UOM) was also estimated.

WTD reconstruction

Testate amoeba WTD reconstructions were performed using the Rioja package (Juggins, 2015) in R version 3.2.4 (R Core Team, 2014). The modern training set contained 59 testate amoeba taxa from 145 samples collected from the same study sites (Zhang et al., 2017). A tolerance-downweighted weighted averaging with inverse deshrinking based model was applied and z scores of the reconstructed WTD values were then calculated over the total length of all the cores to illustrate hydrological changes ($z > 0$ indicates drier than average conditions and $z < 0$ indicates wetter than average conditions; $\Delta z = 1$ represents 8.14 cm WTD range in our dataset), as the reconstructions may poorly represent actual magnitude of water table changes (Swindles et al., 2015c). Model testing and validation are discussed in Zhang et al. (2017).

Results

Chronology and vertical peat growth

Age-depth models show that peat accumulation rates have not been consistent between the study sites over the last few millennia (Fig. 2, Table 1). The thickness of active layers in four sites ranged from 31 cm to 45 cm and basal ages of active layers ranged from 1485 to 7230 cal. BP. In most cases, 25-30 cm peat thickness covered the last millennium, except in Seida where only 7 cm of peat has accumulated during the last millennium. Mean peat accumulation rates over the last millennium ranged from 0.10 to 0.81 mm/year. Vertical growth has been slower at Seida and Kilpisjärvi when compared to Indico and Kevo.

Testate amoeba assemblages and reconstructed WTD

In total, 35 testate amoeba taxa were found in the four study sites. The most dominant taxa for all sites were *Diffugia pristis*, *Pseudodiffugia fulva* type, *P. fascicularis* type and *Trigonopyxis minuta* type (Fig. 3). In Indico *Archerella flavum*, *Cyclopyxis arcelloides* type, *D. pulex*, *Hyalosphenia minuta* and *Nebela militaris* type were also occasionally abundant, while in Seida *Assulina muscorum*, *C. arcelloides* type and *Trinema/Corythion* type were present abundantly. In Kevo *Trinema/Corythion* type was dominant in the topmost samples while in Kilpisjärvi the samples were dominated by *Arcella catinus*.

Three cores were analysed from Indico (Ind1-3), Russia. The testate amoeba assemblages of core Ind1 (Fig. 3a) were first dominated by *P. fulva* type and *D. pristis* at 985 cal. BP. After that until ca. 445 cal. BP *P. fulva* type was the most abundant. Between ca. 445 and -30 cal. BP, *P. fulva* type, *P. fascicularis*

type and *C. arcelloides* type were dominant. *A. flavum* and *A. seminulum* were frequently encountered in samples before -58 cal. BP, after which the proportion of *H. minuta* increased. WTD reconstructions showed that wet conditions occurred at 985 cal. BP, after which relatively dry conditions persisted, with only slight fluctuations before ca. 10 cal. BP. At ca. 10 cal. BP, a change from dry to wet conditions was detected. After a ca. 50-year wet phase, a gradual transition from wet to dry occurred.

The bottom part of core Ind2 (Fig. 3b) was a mixture of peat and sand and testate amoeba were absent or scarce, so testate amoeba data were available only from ca. 430 cal. BP onwards. The assemblages were dominated by *C. arcelloides* type and *P. fulva* type between ca. 430 and 10 cal. BP but towards the core surface *N. militaris* type became the dominant taxon. WTD reconstructions showed a dry-wet shift at ca. 175 cal. BP and a wet-dry shift at ca. 0 cal. BP. During the period 175-0 cal. BP, conditions were generally wet, but fluctuating. Since ca. 0 cal. BP an obvious drying trend prevailed.

In core Ind3 (Fig. 3c), *D. pulex* and *P. fulva* type dominated the assemblages between ca. 1020 and 950 cal. BP. Then *T. minuta* type became abundant until ca. 490 cal. BP after which *D. pristis* and *A. flavum* were the most abundant taxa until ca. 215 cal. BP. After that, *D. pristis*, *N. militaris* type and *T. minuta* type were the most common taxa. The WTD reconstruction showed very dry conditions prevailed until ca. 400 cal. BP, when an obvious dry to wet shift occurred. However, the dominance of the medium wet indicator *D. pristis* (Zhang et al., 2017) suggests only relatively wet conditions. Starting from this shift, a slight wet to dry trend persisted until present-day.

At Seida (Fig. 3d), testate amoeba assemblages around 1060 cal. BP were dominated by *P. fulva* type, while between ca. 1060 and 350 cal. BP *D. pristis* and *A. muscorum* were the most abundant taxa. Relatively wet conditions were inferred between ca. 650 and 350 cal. BP and after 350 cal. BP, *A. muscorum*, *C. arcelloides* type and *Trinema/Corythion* type were the dominant taxa. WTD reconstructions indicated that this site was persistently dry.

At Kevo (Fig. 3e), the assemblage was dominated by *P. fulva* type for the period ca. 1140-100 cal. BP, then *T. minuta* type and *T. arcula* type became abundant between ca. 100 to -20 cal. BP. Towards the surface, *T. minuta* type together with *Trinema/Corythion* type were the most abundant taxa. WTD reconstructions showed that dry conditions existed through the core with a relatively wet event recorded at ca. 550 cal. BP. A drying trend prevailed from ca. 50 cal. BP until present.

At Kilpisjärvi (Fig. 3f), the assemblages generally resembled those of Kevo but the timing of comparable assemblage change differed. *D. pristis*, *P. fulva* type and *P. fascicularis* type were abundant between ca. 1080 and 450 cal. BP. Large proportions of *D. pristis* and *T. minuta* type were recorded between ca. 450 and 0 cal. BP, with *A. catinus* and *T. minuta* types dominant towards recent times. Interestingly, some samples (18-23 cm) contained large quantities of diatoms including taxa such as *Pinnularia major*,

Cymboplectra subcuspidata, *Eunotia praerupta*, *Eunotia serra* and *Brachysira vitrea*. The amount of diatoms was so overwhelming that testate amoeba could not be reliably counted or identified, so these samples were omitted from the WTD reconstruction. WTD reconstructions suggested a relatively wet phase *ca.* 650–450 cal. BP after which, dry but slightly fluctuating conditions persisted until the present.

Vegetation, presence of permafrost and microtopographical evolutions

Plant assemblages varied between the cores (Fig. 3). Plant composition data were used to classify the contemporary habitat conditions and to infer the presence/absence of permafrost (e.g., Oksanen, 2006; Pelletier et al., 2017). In general, we interpret that communities dominated by sedges and brown mosses indicate permafrost-free/thaw habitats while highly decomposed peat with ericaceous/woody remains sometimes accompanied by lichens and fungi sclerotia indicate peat accumulated on top of permafrost following the up-heave of the peatland surface. Though in general *Sphagna* assemblages are used to shed light on moisture conditions they can also help to identify the presence or absence of permafrost. Temporal permafrost melt may create suitable conditions for wet *Sphagna* but these species may also represent permafrost-free hollow conditions. Dry *Sphagna* may grow on top of permafrost hummocks, but equally on permafrost-free hummocks. In addition, though sedges are considered non-permafrost species, some species such as *Eriophorum* spp. can grow on peat plateaus, thus more than a single indicator is usually needed to identify potential presence of permafrost.

At Indico, between 1300 and 985 cal. BP, hummock shrub vegetation dominated in Core Ind1 (Fig. 3a), probably indicating presence of permafrost. At around 985 cal. BP abundant sedge remains indicate wet conditions, which in turn suggest permafrost free conditions, i.e. permafrost melting. After this, until *ca.* 10 cal. BP, a mixed sedge-shrub phase, accompanied by fungi sclerotia, prevailed and peat was highly decomposed. These together suggest re-establishment of permafrost. From *ca.* 10 to -40 cal. BP, a wet hollow phase, dominated by *S. majus* and *Warnstorfia* spp., occurred and this might indicate temporary melting of permafrost. This wet phase was followed by hummock conditions with *S. fuscum*, suggesting permafrost re-aggradation.

Ind2 (Fig. 3b) had a similar succession history, yet the timing differed. A highly decomposed Ericales stage with presence of fungi sclerotia between 1725 and 175 cal. BP was followed by *Eriophorum vaginatum* dominated phase at *ca.* 175 cal. BP. After that, a wetter lawn stage dominated by *S. rubellum* prevailed until *ca.* 30 cal. BP. This pattern suggests alternating permafrost aggradation and melting. Similarly, the near-surface layers were dominated by *S. fuscum*, indicating permafrost re-establishment.

Ind3 (Fig. 3c) vegetation succession differed from the other two Indico records. A highly

decomposed Ericales stage occupied peat layers dated to *ca.* 1020-880 cal. BP suggesting hummock conditions on top of permafrost. Interestingly, after 880 cal. BP there was a community shift where Ericales were replaced by other hummock communities, now dominated by *S. fuscum*. This phase lasted until *ca.* 235 cal. BP. Due to a limited amount of material, we have no continuous plant macrofossil data for the time-window from 215 cal. BP to present day (-52 cal. BP). Currently dwarf shrubs Ericales grow at the coring location.

At Kevo (Fig. 3e), a mixed sedge-shrub vegetation characterised the entire peat core, suggesting that no major hydrological changes have taken place in the recent past. However, after *ca.* 380 cal. BP the plant mixture was accompanied by lichens probably suggesting permafrost conditions.

At Kilpisjärvi (Fig. 3f), before *ca.* 790 cal. BP sedges were the most dominant taxa but occasionally accompanied by other taxa such as Bryophyta spp. This community suggests a typical permafrost-free fen. The short period between *ca.* 790 and 550 cal. BP was dominated by hummock species *S. fuscum*. The following stage, which started at *ca.* 550 cal. BP and lasted until present was dominated by Ericales spp. and indicated relatively stable hummocky conditions on top of permafrost.

Discussion

MCA-induced permafrost thaw and desiccation

In NE European Russia, extensive regional-scale permafrost aggradation occurred from *ca.* 2200 cal. BP onwards (Hugelius et al., 2012; Routh et al., 2014). Therefore, we should be able to detect potential MCA-induced permafrost dynamics and hydrological changes in our Russian cores. Our records suggest that at first, the MCA warming resulted in permafrost melting and consequent establishment of fen-type communities or *Sphagnum*, which corresponds to previous European Russian studies (Routh et al., 2014).

At Indico (Ind1) there was a vegetation change from shrub vegetation to sedges, corresponding with the wet conditions reconstructed from testate amoebae (Figs. 3a and 4). Core Ind3 shows a transition from shrub community to *S. fuscum* at *ca.* 900 cal. BP. (Figs. 3c and 4). This kind of *Sphagnum* establishment has been proposed to be a result of warming and altered peatland hydrology and chemistry (Loisel and Yu, 2013). However, here the relatively dry conditions implied by *S. fuscum* contrasts our first hypothesis, possibly due to only partial permafrost thaw. Wet communities were replaced by shrub communities and supported by testate amoeba reconstructed dry conditions which prevailed for the latter part of the MCA (Figs. 3a and 3c). This phenomenon may either result from melt water drainage (Wilson et al., 2017), or be caused by increased evaporation (Swindles et al., 2015a).

In Fennoscandia, our results suggest that Kevo and Kilpisjärvi peatlands stayed permafrost free until *ca.* 600 cal. BP (see also Oksanen 2006). During the MCA, a relatively dry habitat prevailed at Kevo, while

at Kilpisjärvi a wet fen prevailed (Figs. 3e and 3f). Interestingly, the samples from Kilpisjärvi dated *ca.* 970-630 cal. BP contained large amounts of diatoms and chronologically this clearly wet phase corresponds to a diatom bloom event reported from a northern Swedish peatland (Kokfelt et al., 2009; 2016). Kokfelt et al. (2016) suggested that this wet phase was likely due to the Samalas volcanic eruption in AD 1257 (693 cal. BP) and consequent acid deposition, which resulted in changes in vegetation. At around 790 cal. BP, *S. fuscum* established at the expense of previous rich fen plant communities and this was possibly triggered by volcanic impact rather than permafrost aggradation. However, none of the other peat sections analyzed for this study have diatom-rich layers or conspicuous plant community or moisture shifts dated to around the time of the eruption. During this time period typically dry shrubby conditions prevailed in the other sites, which may have been less sensitive to acid deposition.

LIA-induced permafrost aggradation and drying

In NE European Russia, in line with our second hypothesis, plant data suggest relatively stable dry hummocky habitats during the LIA, whereas testate amoeba data mainly indicate dry conditions, with occasional wet phases (Figs. 3 and 4). The discrepancies between the two proxies suggest testate amoeba are more sensitive to environmental changes than plant communities (Gałka et al., 2017b; Loisel and Garneau, 2010; Välranta et al., 2012). These synchronous wet shifts in testate amoeba records at around 450-400 and 175 cal. BP (Fig. 4) contradict our second hypothesis of dry LIA conditions. However, the timing of wet phases corresponds to many other wet records registered, for example, in parts of northwest and central Europe (Charman et al., 2006; Gałka et al., 2014; Välranta et al., 2007). These climate-caused wet interruptions failed to trigger vegetation changes with the exception of the Ind2 record, which showed a plant community change from shrubs to sedges dated to c. 175 cal. BP. This possibly suggests a greater sensitivity of peatland margins to environmental changes, as core Ind2 was collected from a more marginal location than Ind1 and 3.

Unlike at Indico and Seida, the beginning of LIA at Kilpisjärvi and Kevo seems to have been wet, which corresponds to the humid climate recorded in other parts of Finland (Välranta et al. 2007 and references therein). Consistent with our second hypothesis, conditions subsequently shift and remain dry for the rest of the LIA *ca.* 550-100 cal. BP, most evident in testate amoeba records. Plant macrofossil data from Kilpisjärvi also support this shift by showing a vegetation change from *Sphagnum* domination to a dwarf shrub community, whilst at Kevo the drying reflected by testate amoeba data failed to cause clear vegetation changes (Figs. 3e and 3f). In contrast, according to previous studies from Kevo (e.g., Oksanen 2006), LIA triggered permafrost initiation led to dry elevated peat surfaces and vegetation changes, highlighting that one single peat core sometimes cannot capture a comprehensive regional story

(University of Leeds Peat Club 2017). At Kilpisjärvi, a marked change to dry conditions indicated by testate amoeba records happened around 175 cal. BP but this is absent at Kevo. This dry phase contrasts the wet shifts at Indico and Seida, suggesting that the drivers of these changes were more regional in scale.

Implications of recent warming

Interestingly, our data consistently suggest a habitat change towards drier communities in recent decades, contradicting our first hypothesis that warming results in wetting. The drying is reflected as a change from wet *Sphagna* to dry *Sphagna* (Ind1 and 2), from *Sphagnum* spp. to Ericales shrubs (Ind3) or by an appearance of lichens and dry bryophyte taxa (Kev BS; Fig. 3). Additional testate amoeba data from Seida, Russia also repeat this pattern (Fig. S1). Chronologically, this habitat change corresponds to extensive permafrost degradation reported for the last *ca.* 50 years elsewhere (Sannel and Kuhry, 2011; Swindles et al., 2015a). Local instrumental temperature data from both regions show increasing mean annual temperatures in recent decades (Bekryaev et al., 2010; Bulygina and Razuvaev, 2012; Mikkonen et al., 2015) and warming is projected to continue (Collins et al., 2013). This may have two-fold consequences for permafrost peatlands: accelerated wetting due to thawing of permafrost but followed by desiccation afterwards due to draining and/or an increase in evapotranspiration. Such dynamics were recorded in Ind1 and Ind2 for the recent period, where permafrost thawing caused wet *S. majus* and *S. rubellum* establishment, which were later replaced by dry *S. fuscum*. The final permafrost degradation could lead to a formation of a northern fen-type environment (Swindles et al. 2015a), but only of the surface falls in surface height further as a result of loss of ice.

Conclusions

Our study emphasises the complex nature and variable sensitivity of permafrost peatlands even within a single site, and highlights the need for a multiproxy approach to environmental change reconstructions. Although hydrological and vegetation reconstructions of six cores showed some core-specific dynamics, when put together our data suggest that in general, LIA conditions were dry, supporting hummocky conditions on top of permafrost. Furthermore, we infer that conspicuous short wet events occurred as a result of the MCA and recent warming, which triggered permafrost thawing. However, some of the hydrological conditions during the MCA were drier than those of during the LIA and recent warming is associated with drier conditions across all sites even where thawing initially led to wetter conditions. The changes towards drier conditions during both the MCA and over the last 150 years suggest that evapotranspiration is an important factor in regulating surface peatland moisture conditions during warm

periods in the subarctic.

The hydrological changes during the most recent warming led to especially pronounced drying of the peat surfaces following thawing, even where initial thaw caused temporarily wetter surfaces. We suggest that drying is more likely to occur where limited permafrost is present, because initial increased surface wetness caused by thawing and surface collapse will be relatively minor, and can revert to drier conditions driven by increased evapotranspiration. Whilst it is likely that continued future warming will result in extensive permafrost degradation and subsequent increased surface wetness and Arctic fen development at the landscape-level, our data show that permafrost peatland ecosystems may also respond in more complex ways, including drying. Future changes in precipitation and evapotranspiration are more uncertain than temperature rise, but may be critical in determining future hydrology and vegetation shifts in permafrost peatlands.

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References

Abbott, B.W., Jones, J.B., Schuur, E.A.G., Chapin III, F.S., Bowden, W.B., Bret-Harte, M.S., Epstein, H.E., Flannigan, M.D., Harms, T.K., Hollingsworth, T.N., Mack, M.C., McGuire, A.D., Natali, S.M., Rocha, A.V., Tank, S.E., Turetsky, M.R., Vonk, J.E., Wickland, K.P., Aiken, G.R., Alexander, H.D., Amon, R.M.W., Benscoter, B.W., Bergeron, Y., Bishop, K., Blarquez, O., Bond-Lamberty, B., Breen, A.L., Buffam, I., Cai, Y.H., Carcaillet, C., Carey, S.K., Chen, J.M., Chen, H.Y.H., Christensen, T.R., Cooper, L.W., Cornelissen, J.H.C., de Groot, W.J., DeLuca, T.H., Dorrepaal, E., Fetcher, N., Finlay, J.C., Forbes, B.C., French, N.H.F., Gauthier, S., Girardin, M.P., Goetz, S.J., Goldammer, J.G., Gough, L., Grogan, P., Guo, L.D., Higuera, P.E., Hinzman, L., Hu, F.S., Hugelius, G., Jafarov, E.E., Jandt, R., Johnstone, J.F., Karlsson, J., Kasischke, E.S., Kattner, G., Kelly, R., Keuper, F., Kling, G.W., Kortelainen, P., Kouki, J., Kuhry, P., Laudon, H., Laurion, I., Macdonald, R.W., Mann, P.J., Martikainen, P.J., McClelland, J.W., Molau, U., Oberbauer, S.F., Olefeldt, D., Paré, D., Parisien, M-A., Payette, S., Peng,

397 C.H., Pokrovsky, O.S., Rastetter, E.B., Raymond, P.A., Raynolds, M.K., Rein, G., Reynolds, J.F., Robard,
 398 M., Rogers, B.M., Schädel, C., Schaefer, K., Schmidt, I.K., Shvidenko, A., Sky, J., Spencer, R.G.M.,
 399 Starr, G., Striegl, R.G., Teisserenc, R., Tranvik, L.J., Virtanen, T., Welker, J.M., Zimov, S., 2016. Biomass
 400 offsets little or none of permafrost carbon release from soil, streams, and wildfire: an expert assessment.
 401 Environ. Res. Lett. 11, doi:10.1088/1748-9326/11/3/034014.
 402 Ali, A.A., Ghaleb, B., Garneau, M., Asnong, H., Loisel, J., 2008. Recent peat accumulation rates in
 403 minerotrophic peatlands of the Bay James region, Eastern Canada, inferred by ^{210}Pb and ^{137}Cs
 404 radiometric techniques. Appl. Radiat. Isot. 66, 1350-1358.
 405 Amesbury, M.J., Swindles, G.T., Bobrov, A., Charman, D.J., Holden, J., Lamentowicz, M., Mallon, G.,
 406 Mazei, Y., Mitchell, E.A.D., Payne, R.J., Roland, T.P., Turner, T.E., Warner, B.G., 2016. Development of
 407 a new pan-European testate amoeba transfer function for reconstructing peatland palaeohydrology. Quat.
 408 Sci. Rev. 152, 132-151.
 409 Appleby, P.G., Oldfield, F., 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of
 410 unsupported ^{210}Pb to the sediment. Catena 5, 1-8.
 411 Barnett, R.L., Charman, D.J., Gehrels, W.R., Saher, M.H., Marshall, W.A., 2013. Testate amoebae as sea-
 412 level indicators in Northwestern Norway: developments in sample preparation and analysis. Acta
 413 Protozool. 52, 115-128.
 414 Bekryaev, R.V., Polyakov, I., Alexeev, V.A., 2010. Role of polar amplification in long-term surface air
 415 temperature variations and modern arctic warming. J. clim. 23, 3888-3906.
 416 Blaauw, M., 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. Quat.
 417 Geochronol. 5, 512-518.
 418 Booth, R.K., Lamentowicz, M., Charman, D.J., 2010. Preparation and analysis of testate amoebae in
 419 peatland palaeoenvironmental studies. Mires and Peat 7, 1-7.
 420 Bosio, J., Johansson, M., Callaghan, T.V., Johansen, B., Christensen, T.R., 2012. Future vegetation
 421 changes in thawing subarctic mires and implications for greenhouse gas exchange-a regional assessment.
 422 Clim. Change 115, 379-398.
 423 Brown, J., Ferrians, O.J., Jr., Heginbottom, J.A., Melnikov, E.S., 1998. revised February 2001. Circum-
 424 arctic map of permafrost and ground ice conditions. Boulder, CO: National Snow and Ice Data Center.
 425 Digital media.
 426 Brown, J., Romanovsky, V.E., 2008. Report from the International Permafrost Association: State of
 427 Permafrost in the First Decade of the 21st Century. Permafrost Periglacial Process. 19, 255-260.
 428 Bulygina, O.N., Razuvaev, V.N., 2012. Daily temperature and precipitation data for 518 Russian
 429 meteorological stations, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory,

430 U.S. Department of Energy, Oak Ridge, Tennessee, doi:10.3334/CDIAC/cli.100.

431 Carroll, P., Crill, P., 1997. Carbon balance of a temperate poor fen. *Glob. Biogeochem. Cycle* 11, 349-
432 356.

433 Charman, D.J., Beilman, D.W., Blaauw, M., Booth, R.K., Brewer, S., Chambers, F.M., Christen, J.A.,
434 Gallego-Sala, A., Harrison, S.P., Hughes, P.D.M., Jackson, S.T., Korhola, A., Mauquoy, D., Mitchell,
435 F.J.G., Prentice, I.C., van der Linden, M., De Vleeschouwer, F., Yu, Z.C., Alm, J., Bauer, I.E., Corish,
436 Y.M.C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols,
437 J.E., Nieminen, T.M., MacDonald, G.M., Phadtare, N.R., Rausch, N., Sillasoo, U., Swindles, G.T.,
438 Tuittila, E.S., Ukonmaanaho, L., Välranta, M., van Bellen, S., van Geel, B., Vitt, D.H., Zhao, Y., 2013.
439 Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences* 10,
440 929-944.

441 Charman, D.J., Blundell, A., ACCROTELM members., 2007. A new European testate amoebae transfer
442 function for palaeohydrological reconstruction on ombrotrophic peatlands. *J. Quat. Sci.* 22, 209-221.

443 Charman, D.J., Blundell, A., Chiverrell, R.C., Hendon, D., Langdon, P.G., 2006. Compilation of non-
444 annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table
445 reconstructions from northern Britain. *Quat. Sci. Rev.* 25, 336-350.

446 Charman, D.J., Gehrels, W.R., Manning, C., Sharma, C., 2010. Reconstruction of recent sea-level change
447 using testate amoebae. *Quat. Res.* 73, 208-219.

448 Charman, D.J., Hendon, D., Woodland, W.A., 2000. The Identification of Testate Amoebae (Protozoa:
449 Rhizopoda) in Peats. Quaternary Research Association, Oxford.

450 Collins, M., Knutti, R., Arblaster, J., Dufresne, J-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski,
451 W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term
452 Climate Change: Projections, Commitments and Irreversibility, In: Stocker, T.F., Qin, D., Plattner, G-K.,
453 Tignor, M., Allen, S.K., Boschung, J., Nauels, A, Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change*
454 *2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
455 *the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United
456 Kingdom and New York, NY, USA.

457 Cook, E.D., Esper, J., D'Arrigo, R.D., 2004. Extra-tropical Northern Hemisphere land temperature
458 variability over the past 1000 years. *Quat. Sci. Rev.* 23, 2063-2074.

459 Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and
460 feedbacks to climate change. *Nature* 440, 165-173.

461 Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T.V., Aerts, R.,
462 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature*

463 460, 616-619.

464 Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies
465 for reconstructing past temperature variability. *Science* 295, 2250-2253.

466 Frolking, S., Roulet, N.T., 2007. Holocene radiative forcing impact of northern peatland carbon
467 accumulation and methane emissions. *Glob. Change Biol.* 13, 1079-1088.

468 Gałka, M., Szal, M., Watson, E.J., Gallego-Sala, A., Amesbury, M.J., Charman, D.J., Roland, T.P.,
469 Turner, T.E., Swindles, G.T., 2017a. Vegetation Succession, Carbon Accumulation and Hydrological
470 Change in Subarctic Peatlands, Abisko, Northern Sweden. *Permafrost Periglacial Process.* doi:
471 10.1002/ppp.1945.

472 Gałka, M., Tobolski, K., Górka, A., Lamentowicz, M., 2017b. Resilience of plant and testate amoeba
473 communities after climatic and anthropogenic disturbances in a Baltic bog in Northern Poland:
474 Implications for ecological restoration. *Holocene* 27, 130-141.

475 Gałka, M., Tobolski, K., Górka, A., Milecka, K., Fiałkiewicz-Kozieł, B., Lamentowicz, M.,
476 2014. Disentangling the drivers for the development of a Baltic bog during the Little Ice Age in northern
477 Poland. *Quat. Int.* 328–329, 323–337.

478 Hanhijärvi, S., Tingley, M.P., Korhola, A., 2013. Pairwise comparisons to reconstruct mean temperature
479 in the Arctic Atlantic Region over the last 2,000 years. *Clim. Dyn.* 41, 2039–2060.

480 Holmquist, J.R., Finkelstein, S.A., Garneau, M., Massa, C., Yu, Z.C., MacDonald, G.M., 2016. A
481 comparison of radiocarbon ages derived from bulk peat and selected plant macrofossils in basal peat
482 cores from circum-arctic peatlands. *Quat. Geochronol.* 31, 53-61.

483 Hugelius, G., Routh, J., Kuhry, P., Crill, P., 2012. Mapping the degree of decomposition and thaw
484 remobilization potential of soil organic matter in discontinuous permafrost terrain. *J. Geophys. Res.* 117,
485 G02030, doi:10.1029/2011JG001873.

486 IPCC, 2013. Summary for Policymakers, In: Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M., Allen,
487 S.K., Boschung, J., Nauels, A, Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical*
488 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
489 *Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY,
490 USA.

491 Johansson, M., Åkerman, J., Keuper, F., Christensen, T.R., Lantuit, H., Callaghan, T.V., 2011. Past and
492 present permafrost temperatures in the Abisko Area: redrilling of boreholes. *Ambio* 40, 558-565.

493 Juggins, S., 2015. Rioja: Analysis of Quaternary ScienceData, R package version (0.9-5). ([http://cran.r-](http://cran.r-project.org/package=rioja)
494 [project.org/package=rioja](http://cran.r-project.org/package=rioja)).

495 Kokfelt, U., Muscheler, R., Mellstrom, A., Struyf, E., Rundgren, M., Wastegard, S., Hammarlund, D.,

496 2016. Diatom blooms and associated vegetation shifts in a subarctic peatland: responses to distant
 497 volcanic eruptions? *J. Quat. Sci.* 31, 723-730.

498 Kokfelt, U., Struyf, E., Randsalu, L., 2009. Diatoms in peat—Dominant producers in a changing
 499 environment? *Soil Biol. Biochem.* 41, 1764-1766.

500 Koven, C.D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G.,
 501 Tarnocai, C., 2011. Permafrost carbon-climate feedbacks accelerate global warming. *Proc. Natl. Acad.*
 502 *Sci. U.S.A.* 108, 14769-14774.

503 Lamarre, A., Garneau, M., Asnong, H., 2012. Holocene paleohydrological reconstruction and carbon
 504 accumulation of a permafrost peatland using testate amoeba and macrofossil analyses, Kuujjuarapik,
 505 subarctic Quebec, Canada. *Rev. Palaeobot. Palynology* 186, 131-141.

506 Loisel, J., Garneau, M., 2010. Late Holocene paleoecohydrology and carbon accumulation estimates
 507 from two boreal peat bogs in eastern Canada: Potential and limits of multi-proxy archives. *Paleogeogr.*
 508 *Paleoclimatol. Paleoecol.* 291, 493-533.

509 Loisel, J., Yu, Z.C., 2013. Recent acceleration of carbon accumulation in a boreal peatland, south central
 510 Alaska. *J. Geophys. Res. Biogeosci.* 118, 41-53.

511 Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., González Rouco, J.F., Jansen,
 512 E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas,
 513 M., Shao, X., Timmermann, A., 2013. Information from Paleoclimate Archives, In: Stocker, T.F., Qin,
 514 D., Plattner, G-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.),
 515 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
 516 *Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press,
 517 Cambridge, United Kingdom and New York, NY, USA.

518 Mathijssen, P.J.H., 2016. Holocene carbon dynamics and atmospheric radiative forcing of different types
 519 of peatlands in Finland. PhD thesis, Dep. Of Environ. Sci., Univ. of Helsinki, Finland. [Available at
 520 <http://hdl.handle.net/10138/161250>.]

521 Mathijssen, P.J.H., Kähkölä, N., Tuovinen, J-P., Lohila, A., Minkkinen, K., Laurila, T., Väiliranta, M.,
 522 2017. Lateral expansion and carbon exchange of a boreal peatland in Finland resulting in 7000 years of
 523 positive radiative forcing. *J. Geophys. Res. Biogeosci.*, doi: 10.1002/2016JG003749.

524 Mikkonen, S., Laine, M., Mäkelä, H.M., Gregow, H., Tuomenvirta, H., Lahtinen, M., Laaksonen, A.,
 525 2015. Trends in the average temperature in Finland, 1847-2013. *Stoch. Environ. Res. Risk Assess.*, 29,
 526 1521-1529.

527 Oksanen, P.O., 2006. Holocene development of the Vaisjeaggi palsa mire, Finnish Lapland. *Boreas* 35,
 528 81-95.

529 Oksanen, P.O., Kuhry, P., Alekseeva, R.N., 2001. Holocene development of the Rogovaya River peat
 530 plateau, European Russian Arctic. *Holocene* 11, 25-40.
 531 Ovenden, L., 1990. Peat accumulation in Northern wetlands. *Quat. Res.* 33, 377-386.
 532 Pelletier, N., Talbot, J., Olefeldt, D., Turetsky, M., Blodau, C., Sonnentag, O., Quinton, W.L., 2017.
 533 Influence of Holocene permafrost aggradation and thaw on the paleoecology and carbon storage of a
 534 peatland complex in northwestern Canada. *Holocene*, doi: 10.1177/0959683617693899.
 535 Pirinen, P., Simola, H., Aalto, J., Kaukoranta, J.-P., Karlsson, P., Ruuhela, R., 2012. Tilastoja Suomen
 536 ilmastosta 1981–2010 (Climatological statistics of Finland 1981–2010). Finnish Meteorological Institute
 537 Reports, 1.
 538 R Core Team, 2014. R: A language and environment for statistical computing. R Foundation for
 539 Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>.
 540 Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H.,
 541 Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hafflidason, H., Hajdas, I., Hatté, C.,
 542 Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu,
 543 M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht,
 544 J., 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0-50,000 years cal BP. *Radiocarbon*
 545 55, 1869-1887.
 546 Repo, M.E., Susiluoto, S., Lind, S.E., Jokinen, S., Elsakov, V., Biasi, C., Virtanen, T., Martikainen, P.J.,
 547 2009. Large N₂O emissions from cryoturbated peat soil in tundra. *Nat. Geosci.* 2, 189-192.
 548 Routh, J., Hugelius, G., Kuhry, P., Filley, T., Tillman, P.K., Becher, M., Crill, P., 2014. Multi-proxy study
 549 of soil organic matter dynamics in permafrost peat deposits reveal vulnerability to climate change in the
 550 European Russian Arctic. *Chem. Geol.* 368, 104-117.
 551 Sannel, A.B.K., Hugelius, G., Jansson, P., Kuhry, P., 2016. Permafrost warming in a Subarctic peatland-
 552 which meteorological controls are most important? *Permafrost Periglacial Process.* 27, 177-188.
 553 Sannel, A.B.K., Kuhry, P., 2011. Warming-induced destabilization of peat plateau/thermokarst lake
 554 complexes. *J. Geophys. Res. Biogeosci.* 116, G03035, doi:10.1029/2010JG001635.
 555 Schadel, C., Bader, M.K.F., Schuur, E.A.G., Biasi, C., Bracho, R., Capek, P., De Baets, S., Diakova, K.,
 556 Ernakovich, J., Estop-Aragones, C., Graham, D.E., Hartley, I.P., Iversen, C.M., Kane, E.S., Knoblauch,
 557 C., Lupascu, M., Martikainen, P.J., Natali, S.M., Norby, R.J., O'Donnell, J.A., Chowdhury, T.R.,
 558 Santruckova, H., Shaver, G., Sloan, V.L., Treat, C.C., Turetsky, M.R., Waldrop, M.P., Wickland, K.P.,
 559 2016. Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nat. Clim.*
 560 *Chang.* 6, 950-954.
 561 Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann,

562 S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E.,
 563 Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J.G., Zimov, S.A., 2008. Vulnerability of Permafrost
 564 Carbon to Climate Change: Implications for the Global Carbon Cycle. *BioScience* 58, 701-714.
 565 Swindles, G.T., Morris, P.J., Baird, A.J., Blaauw, M., Plunkett, G., 2012. Ecohydrological feedbacks
 566 confound peat-based climate reconstructions. *Geophys. Res. Lett.* 39, doi:10.1029/2012GL051500.
 567 Swindles, G.T., Morris, P.J., Mullan, D., Watson, E.J., Turner, T.E., Roland, T.P., Amesbury, M.J., Kokfelt,
 568 U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D.J., Sanderson, N., Garneau, M., Carrivick,
 569 J.L., Woulds, C., Holden, J., Parry, L., Galloway, J.M., 2015a. The long-term fate of permafrost peatlands
 570 under rapid climate warming. *Sci. Rep.* 5, doi: 10.1038/srep17951.
 571 Swindles, G.T., Amesbury, M.J., Turner, T.E., Carrivick, J.L., Woulds, C., Raby, C., Mullan, D., Roland,
 572 T.P., Galloway, J.M., Parry, L., Kokfelt, U., Garneau, M., Charman, D.J., Holden, J., 2015b. Evaluating
 573 the use of testate amoebae for palaeohydrological reconstruction in permafrost peatlands. *Paleogeogr.*
 574 *Paleoclimatol. Paleoecol.* 424, 111-122.
 575 Swindles, G.T., Holden, J., Raby, C.L., Turner, T.E., Blundell, A., Charman, D.J., Menberu, M.W., Kløve,
 576 B., 2015c. Testing peatland water-table depth transfer functions using high-resolution hydrological
 577 monitoring data. *Quat. Sci. Rev.* 120, 107-117.
 578 Teltewskoi, A., Beermann, F., Beil, I., Bobrov, A., De Klerk, P., Lorenz, S., Luder, A., Michaelis, D.,
 579 Joosten, H., 2016. 4000 Years of Changing Wetness in a Permafrost Polygon Peatland (Kytalyk, NE
 580 Siberia): A Comparative High-Resolution Multi-Proxy Study. *Permafrost Periglacial Process.* 27, 76-95.
 581 Tremblay, S., Bhiry, N., Lavoie, M., 2014. Long-term dynamics of a palsa in the sporadic permafrost
 582 zone of northwestern Quebec (Canada). *Can. J. Earth Sci.* 51, 500-509.
 583 Tuittila, E-S., Juutinen, S., Froking, S., Välranta, M., Laine, A.M., Miettinen, A., Seväkivi, M-L.,
 584 Quillet, A., Merilä, P., 2012. Wetland chronosequence as a model of peatland development: Vegetation
 585 succession, peat and carbon accumulation. *Holocene* 23, 25-35.
 586 University of Leeds Peat Club: Bacon, K.L., Baird, A.J., Blundell, A., Bourgault, M-A., Chapman, P.J.,
 587 Dargie, G., Dooling, G.P., Gee, C., Holden, J., Kelly, T., McKendrick-Smith, K.A., Morris, P.J., Noble,
 588 A., Palmer, S.M., Quillet, A., Swindles, G.T., Watson, E.J., Young, D.M., 2017. Questioning ten common
 589 assumptions about peatlands. *Mires Peat* 19, 1-23.
 590 Välranta, M., Blundell, A., Charman, D.J., Karofeld, E., Korhola, A., Sillasoo, U., Tuittila, E-S., 2012.
 591 Reconstructing peatland water tables using transfer functions for plant macrofossils and testate amoebae:
 592 A methodological comparison. *Quat. Int.* 268, 34-43.
 593 Välranta, M., Korhola, A., Seppä, H., Tuittila, E.S., Sarmaja-Korjonen, K., Laine, J., Alm, J., 2007.
 594 High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the

595 late Holocene: a quantitative approach. *Holocene* 17, 1093-1107.
 596 Väliranta, M., Salonen, J.S., Heikkilä, M., Amon, L., Helmens, K., Klimaschewski, A., Kuhry, P., Kultti,
 597 S., Poska, A., Shala, S., Veski, S., Birks, H.H., 2015. Plant macrofossil evidence for an early onset of the
 598 Holocene summer thermal maximum in northernmost Europe. *Nat. Commun.* 6, 6809.
 599 Wilson, R., Anchukaitis, Kevin., Briffa, K.R., Büntgen, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J.,
 600 Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krusic, P.J., Linderholm, H.W., Myglan,
 601 V., Osborn, T.J., Rydval, M., Schneider, L., Schurer, A., Wiles, G., Zhang, P., Zorita, E., 2016. Last
 602 millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context.
 603 *Quat. Sci. Rev.* 134, 1-18.
 604 Wilson, R.M., Fitzhugh, L., Whiting, G.J., Frolking, S., Harrison, M.D., Dimova, N., Burnett, W.C.,
 605 Chanton, J.P., 2017. Greenhouse gas balance over thaw-freeze cycles in discontinuous zone permafrost.
 606 *J. Geophys. Res. Biogeosci.* 122, 387-404.
 607 Yu, Z.C., Beilman, D.W., Jones, M.C., 2009. Sensitivity of Northern Peatland Carbon Dynamics to
 608 Holocene Climate Change, in: Baird, A.J., Belyea, L.R. Comas, X., Reeve, A.S., Slater, L.D. (Eds.)
 609 Carbon Cycling in Northern Peatlands. American Geophysical Union, Washington, D.C.. doi:
 610 10.1029/2008GM000822.
 611 Zhang, H, Amesbury, M.J., Ronkainen, T., Charman, D.J., Gallego-Sala, A.V., Väliranta, M., 2016.
 612 Testate amoeba as palaeohydrological indicators in the permafrost peatlands of Northeast European
 613 Russia and Finnish Lapland. *J. Quat. Sci.* doi:10.1002/jqs.2970.
 614 Zuidhoff, F.S., Kolstrup, E., 2000. Changes in Palsa Distribution in Relation to Climate Change in
 615 Laivadalén, Northern Sweden, Especially 1960-1997. *Permafrost Periglacial process.* 11, 55-69.